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WIDE-FIELD EXTENDED-DEPTH DOUBLY TELECENTRIC CATADIOPTRIC OPTICAL SYSTEM FOR DIGITAL IMAGING

DESCRIPTION

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CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U. S. Provisional Application Serial No. 60/198,764,

10   filed April 21, 2000, the entire contents of which are hereby incorporated by reference herein.

BACKGROUND OF THE INVENTION

15   Field of the Invention

The present invention generally relates to optical systems for automated imaging and, more particularly, to optical systems for digital

20   imaging for optical character recognition (OCR), automated inspection, optical metrology (e.g. object identification and classification), machine vision, robotics, bar code readers (BCRs) and the like.

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Description of the Prior Art

Many different types of optical systems including one or more lenses and/or mirrors and

30   structure to maintain or adjust the relative positions of such optical elements have been known for many years for various applications, including telescopes, microscopes and human vision correction. Cameras generally combine such

35   optical systems with an arrangement to position a radiation sensitive film or electronic sensor positioned relative to the focal plane of the

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optical system. Cameras using electronic sensors
have recently become very popular as a substitute
for film-based cameras and have also found
substantial utility in various automated image
5   capture applications such as vision-based control
systems, BCRs and OCR systems.

     Many different types of optical systems are
known and have different properties which may be
of potential relative advantage in particular
10   applications. However, application of some types
of optical systems to purposes in which they might
be otherwise advantageous may be precluded by
corresponding constraints. As a simple example,
large fields of view must generally be provided by
15   wide-angle lenses which characteristically exhibit
substantial distortion that increases with off-
axis angle. Correction of such distortion is
often only possible with expensive aspheric
elements or through the use of image processing
20   which is expensive.

     Long focal length lenses at considerable
distances from an object to be imaged have been
used to restrict the relative change in resolution
over a large change in object position along the
25   optical axis but this can be impractical where
space is a limitation and may require the use of
multiple path-folding mirrors of high optical
quality which are expensive and ultimately reduce
overall image quality because of surface
30   irregularities. This is, at best, only a partial
solution since the resolution will still be
relatively high at relatively closer object
positions thus limiting unnecessarily the ultimate
scan rate of the image capture device. Therefore,
35   some types of lens systems exhibiting some
potentially useful properties have little or no
known practical application and are often, at

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most, of theoretical interest.

So-called telecentric optical systems are exemplary of systems having unique properties but which are severely constrained in application. An article entitled "Optical Design and Specification of Telecentric Optical Systems" by Michael A. Pate, Proc. SPIE, Vol 3482, pp. 877 - 886, June 8 - 12, 1998, which is hereby fully incorporated by reference, notes that the objective lens must be larger than the field of view or object of interest and that telecentric optical systems have principal utility in measurement and fabrication of three-dimensional parts. The article also notes that while telecentric lenses were independently discovered in 1848 (Porro) and 1878 (Abbe), telecentric optical system design is not well known or published; stating that the published literature is "very elementary" and "current optical design literature uses anywhere from one sentence to one paragraph to describe and define telecentric optical system design".

By definition, telecentric optical systems fall into two main categories, image telecentric systems and object telecentric systems. Image telecentric systems have an aperture located at the front focal plane of the objective lens such that the chief ray from any object point passes through the center of the aperture and emerges parallel to the optical axis in image space and perpendicular to the image plane (exit pupil at infinity). Object telecentric systems have an auxiliary lens (or mirror) which is located such that its back focal plane coincides with the entrance pupil of the objective lens such that the chief ray from any object point is parallel to the optical axis in object space (entrance pupil at infinity). These two categories can be combined

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to form a hybrid system known as a doubly
telecentric system. This geometry provides the
theoretical property of providing constant size
imaging over a range of distances of an object

5   from the optical system. Thus the image of an
object formed by a doubly telecentric system will
be substantially isometric or orthographic
(whereas an image made with a non-telecentric
system will have substantially a single vanishing

10   point perspective).

That is, telecentric optical systems, in
practice, fall into two groups and a combination
or hybrid group, each having a combination of
severe constraints. Object telecentric optical

15   systems, which require an auxiliary objective, are
telecentric on the object side of the objective
only and utilize the aperture of the camera
objective lens. Practical use of object
telecentric optical systems relies on depth of

20   field (implying a small aperture and limited
light-gathering ability) and constant focus. As
long as focus does not change, the center of blur
(circle of confusion) of an imaged point from an
object will remain stationary in the image plane

25   as the object being imaged is moved along the lens
system axis.

That is, within a relatively shallow depth of
field and for a field smaller than the auxiliary
lens diameter, the image of an object will be of

30   constant size over a range of axial motion of the
object. However, the property of a constant size
image is lost if the system is refocused in
accordance with such axial motion. Therefore, an
extremely restrictive range of axial motion

35   (within the depth of field at a given object
distance) and object size (limited by the diameter
of the auxiliary lens) must be observed in order

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to render focused detail of the object at constant image size.

As an example of such limitations, U. S. Patent 4,851,698 to Hippenmeyer discloses use of
5   an object telecentric system for measuring separation of features on an object surface. In this case, a well-focused image is apparently of relatively low importance (in connection with a row camera having a linear array of sensors) so
10   long as the image blur allows determination of the respective centers of blurred image features. The lens diameter must also exceed the distance to be measured on the object but can be extended by a factor of ten along a linear zone corresponding to
15   a row of detectors by use of a concave strip mirror. Further, the system must be recalibrated if it is refocused to closer distances than infinity (which will also reduce usable depth of field, referred to therein as a range of
20   sharpness).

So-called image telecentric optical systems are somewhat the reverse of object telecentric systems. Image telecentric systems have an aperture at the front focal plane. However,·
25   unlike object telecentric lenses, alteration of focus does not alter the magnification and size of the image provided that the object and the lens elements remain stationary relative to one another, i.e., if only the image sensor is moved
30   to adjust focus. However, motion of the object along the optical axis results in a change of magnification of the image, focused or unfocused. In essence, an image telecentric lens system has virtually no advantages over an object telecentric
35   lens system and significant further constraints.

Even though known measurement applications use telecentric lens systems at a single focus

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distance, this may be a critical constraint in
regard to some possible applications and further
limits use of object and image telecentric lenses
in applications where a focused image is of

5   importance. The hybrid configuration alluded to
above is referred to as a doubly telecentric
optical system and essentially uses both an image
telecentric objective coaxially located with an
object telecentric objective such that the rear

10   focal plane of the object telecentric objective
coincides with the front focal plane of the image
telecentric objective with the aperture placed at
the juncture of the two focal planes serving as
the exit aperture of the object-side objective and

15   the entrance pupil of the image-side objective.

However, it has generally been considered
that a doubly telecentric system would be
constrained by the constraints characteristic of
both object and image telecentric optical systems,

20   especially by the constraint in the field width
due to limited width of the object-side objective
which is traditionally a refractive lens.
Accordingly, little, if any, practical application
has been envisioned for doubly telecentric optical

25   systems. The properties of doubly telecentric
optical systems do not appear to have been
investigated and appear to be considerably less
well-known than object or image telecentric
systems.

30   In fact, the above-incorporated article,
while otherwise seeking to be a comprehensive
overview of telecentric lens design, does not even
acknowledge the existence of doubly telecentric
optical systems, nor does it include any

35   discussion of the properties or applications of
such a configuration. It is also significant that
while object telecentric and image telecentric

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refractive lenses are commercially available, at
least in small diameters, doubly telecentric
lenses are not similarly available and cannot
reasonably be assembled from commercially
5   available object and image telecentric systems.
The above-incorporated article also
acknowledges that the large lens sizes required by
telecentric optical systems can be extremely
expensive since the cost of a lens generally
10   increases as the cube of the diameter. Therefore,
while the article acknowledges that image
processing by computer is complex and slow,
particularly in correcting for distortions of non-
telecentric lenses used for making optical
15   measurements, such image processing has been more
economical than use of large telecentric optical
systems which do not change magnification with
lens to object distance, at least for measurement
applications.
20   Nevertheless, digital imaging quantizes the
image at least in accordance with scan lines or
the array of sensor areas at which image capture
can occur. With known and well-understood non-
telecentric optical systems, magnification and,
25   hence, resolution vary with changes in distance of
an object from the camera lens or focal plane.
Even with object telecentric lens systems,
resolution will necessarily vary with distance of
the object from the lens in the sense that the
30   image will become defocused with change of
distance between the object and lens outside a
shallow depth of field if the optical system is
operated at a fixed focus or, if the lens is
refocused, magnification and, hence, resolution
35   will change.
This characteristic of most lenses presents a
problem in regard to optical character recognition

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(OCR), bar code readers (BCRs), feature extraction systems and the like which must also operate from data representing a reasonably well-focused image (e.g. systems which compare image features with
5   templates). This comparison, especially in systems including some degree of adaptive processing, requires constant resolution from one image to the next.

Similarly, optical metrology, requires
10   constant image magnification even where the distance between the object of interest and the optical system may not be well-controlled. Variations from these requirements may also affect the performance of other systems such as bar-code
15   readers and optical inspection systems to varying degrees. Magnification variation with depth/distance also causes severe perspective distortion (particularly when providing wide angles of view) which present severe difficulties
20   for machine vision systems such as vision based guidance systems and robotics. Generally, a relatively wide angle of view is required to accommodate the size of objects of interest while maintaining the overall system (object, lens and
25   camera/sensor) at an acceptable size even though, as alluded to above, distortion is usually increased with wide-angle lenses.

It should also be appreciated, in this regard, that there are some environments where the
30   distance between the lens and features of interest on an object inherently varies widely and cannot be controlled. For example, when using OCR systems to read address information on packages of essentially random sizes, the lens to object
35   distance will necessarily vary as widely as the maximum size to be accommodated since some packages could be very thin or short. In the case

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of tall packages which would place the address
information very close to the lens, the dimensions
of the information may exceed the field of view of
the optical system.

5   Further, as OCR and optical metrology
techniques are applied to high throughput systems
such as mail sorting, the digital image processing
overhead to correct for change of magnification
with distance and distortion becomes a major
10   limitation on overall system capacity, even when
very high speed digital data processors are
employed. Such image processing necessarily
carries a substantial computational overhead to
achieve the effect of essentially discarding data
15   and the resolution that data represents and which
could otherwise be utilized to improve machine
vision system performance. Additionally, this
limitation on throughput carries a significant
economic cost in regard to the controlled system
20   which must increasingly be balanced against
optical system cost when high throughput is
required.

     Moreover, OCR, BCR and other machine vision
systems must capture a reasonably well-focused
25   image for further processing. It was noted above
that object telecentric systems cannot be focused
without recalibration of image size and must be
used to image objects in a relatively narrow depth
of field where focus errors are of a tolerable
30   magnitude. Likewise, image telecentric systems
can only be focused at a constant image size by
movement of the image plane whereas traditional
focusing techniques move either the entire lens or
subgroups of elements necessitating movement of
35   the object-side objective in synchrony with the
image-side objective. However, any change in
object position relative to the objective changes

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image magnification. This difficulty of focusing
even image telecentric systems without changing
the magnification is thus seen to be a severe
limitation on applicability of telecentric optical
5 systems to environments where well-focused images
are required.

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SUMMARY OF THE INVENTION

5   It is therefore an object of the present invention to provide an optical system capable of providing constant magnification and resolution of well-focused images over a significant range of focus and object to lens distances and over a wide field of view.

10   It is another object of the invention to provide an optical system for digital image capture and processing that does not require software (or modification thereof) to correct for variable resolution and perspective distortion such as keystone distortions.

15   It is a further object of the invention to provide improved performance and increased throughput of machine vision controlled systems.

In order to accomplish these and other objects of the invention, the present invention in a preferred embodiment provides an optical system

20   comprising a doubly telecentric optical system and a camera. In a particularly preferred embodiment, the camera includes means for shifting a location of an image sensor. In another preferred

25   embodiment, the invention provides an optical system comprising a doubly telecentric optical system having a spherical or aspheric concave mirror or mirror strip as an objective element thereof, an aperture at the juncture of the back

30   focal plane of said mirror and the front focal plane of a traditional camera objective, and a camera including means for shifting a location of an image sensor of a line scan or area scan variety.

35   The invention also provides a machine vision controlled system including a controllable means for performing a function, a doubly telecentric

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optical system having a concave mirror as an
objective element thereof, a camera including
means for shifting a location of an image sensor,
and means for processing data derived from said
5   image sensor to control said controllable means.

In another preferred embodiment, the
invention provides an optical character
recognition system for package imaging
comprising a doubly telecentric optical system.
10 Additionally, the invention provides an optical
character recognition system for article imaging
comprising a doubly telecentric optical system
comprising a concave strip mirror; at least one
conveyor for transporting articles for view by the
15 doubly telecentric optical system; a camera
including a movable image sensor; at least one
planar mirror; at least one partially reflecting
mirror; a light source; at least one chain line;
an image processor for receiving image data from
20 the image sensor of the camera; and a controller.

In a further embodiment, the invention
provides a sorting method for articles having
visible information on a face of each said
article, wherein said articles may be irregularly
25 sized. The steps may comprise: moving, by
automation, each article into a doubly telecentric
optical system, then making an image of the
visible information on each article; recording the
image made of the visible information and
30 computerized processing of said recorded image.
In a particularly preferred embodiment of the
inventive method, zip-code sorting of the
articles is performed.

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BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects and
advantages will be better understood from the
following detailed description of a preferred
embodiment of the invention with reference to the
drawings, in which:

Figure 1 is a schematic illustration of
imaging by a conventional, non-telecentric optical
system,

Figure 2 is a schematic illustration of
imaging by a conventional, object telecentric
optical system,

Figure 3 is a schematic illustration of
imaging by a conventional, image telecentric
optical system,

Figure 4 is a schematic illustration of
imaging by a doubly telecentric optical system in
accordance with the invention, and

Figure 5 schematically depicts a generalized
vision-based (e.g. OCR) system including the
invention.

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DETAILED DESCRIPTION OF A PREFERRED
EMBODIMENT OF THE INVENTION

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Referring now to the drawings, and more particularly to Figure 1, there is schematically shown a conventional lens system 10, having front and rear focal points F, F', imaging objects H1, H2 of the same size at different locations S1, S2 which are different axial distances from lens 10.

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It is understood that H1 and H2 can be representations of the same object positioned at different depths along the optical axis and are shown simultaneously for purposes of comparison. They could also represent two points on a hollow

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object that are axially separated but of the same height. By following the principal rays from the upper ends of the objects H1, H2 it is seen that the image H1' of object H1 at location S1 at the greater of the two axial distances is focused at

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location S1' a short distance behind rear focal point F'. By similarly following the illustrated principal ray from the upper end of object H2, it can be seen that image H2' is focused at a greater distance behind rear focal point F' and that the

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image H2' is much larger than the image H1'.

This difference in size of images of objects at different axial distances from the lens 10 results in magnification and resolution changes in a digital imaging system as an object is placed

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nearer or farther from the lens. This image magnification change results in the image of a three-dimensional object being rendered in perspective with a single vanishing point and is the reason for "keystone" distortion of the shape

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of rectangular objects imaged with conventional lens system 10 as the distance increases away from the lens. Note that if the sensor, 12, is placed

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between images H1' and H2', a blur circle (circle
of confusion) is formed on the sensor for each
defocused image point. The centers of the blur
circles are located at the positions where the
5   principal rays, 14 and 16, intersect the sensor
plane 12. Also note that, in general, these are
two separate points along the sensor.

Referring now to Figures 2 and 3, an object
telecentric optical system and an image
10   telecentric optical system are respectively shown.
While these types of telecentric optical systems
are known and the illustrations thereof are
generalized to convey an understanding thereof, no
feature of either telecentric system, as depicted
15   or described below, is admitted to be prior art in
regard to the present invention.

In the object telecentric system of Figure 2,
the primary objective 22 of the telecentric system
is schematically depicted at M1 which can be
20   either a refractive lens or a mirror (as in the
Hippenmeyer patent discussed above). Objective M1
has front and rear focal points F1, F1',
respectively. Lens 24 is a simplified
representation of the objective lens L1 of a
25   camera C and is located at F1' since it also
serves as the entrance pupil of the camera
objective. Lens 24 (L1) also has front and rear
focal points F2, F2'. The sensor of the camera is
indicated at 26 and can be moved toward or away
30   from F2' to focus the camera.

Two objects H1, H2 of the same size but at
different locations S1, S2 at different distances
from objective 22 are shown as in Figure 1 above.
These two objects can be understood as the same
35   object at two different axial positions or two
points of a single object as explained above for
Figure 1. Images H1', H2' are formed at S1', S2',

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respectively. S1' is depicted as preceding F2'
since H1 is positioned at S1 which is outside of
F1 for illustrative purposes. S2' is depicted as
following F2' since H2 is positioned at S2 which
5   is inside of F1, again, for illustrative purposes.
The far working distance is somewhat
arbitrary but at infinity the primary image is at
F1' and no image can be formed by L1. A sensor 26
located between S1' and S2', approximately as
10   shown, would thus receive a defocused or blurred
image of both H1 and H2 but the rays from the
topmost points of both objects would be centered
within the blurred images at H_T, as can be
observed from principal rays 28. Note that in the
15   object telecentric case, since the principal ray
always passes through F1', located at the entrance
pupil of the camera objective, both images share
the same principal ray, unlike the conventional
case where each image has a distinctly different
20   principal ray.
By the same token, if either H1' or H2' is
brought into focus by movement of image/sensor
plane 26, the resulting image will be of a
different size than the other focused image
25   (and/or H_T) as in the conventional case. However,
for a given location of the image plane 26, the
centers of the blur circles from both images
coincide, unlike the conventional case where they
occur at two distinct points along the sensor.
30   Thus, if the sensor is held fixed within a given
depth of focus, the image magnification is
constant over the entire depth of field which is
typically limited to a very shallow depth. Note
also that the field of view is limited by the
35   diameter of the primary objective.
Referring now to Figure 3, an image
telecentric optical system is shown. Aperture A,

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which serves as the entrance pupil, is on the
object side of the objective lens L. As in Figure
2, two objects H1, H2 of equal size are shown at
different locations S1, S2, respectively, which
5   are at different axial distances from objective
lens L. Front and back focal points F, F' of
objective lens L are shown. The object can be
much larger than the diameter of the lens as in
the conventional case but is illustrated as
10   smaller than lens L for clarity and comparison
with other Figures.

Again, by tracing principal rays 32 and 34
from H1, H2 through the image telecentric lens
system of Figure 3, it is seen that a sensor 36,
15   located as shown, will produce images H1' and H2'
of objects H1 and H2. Both images are of
different size and both are defocused. It will be
noted, however, that, since the principal rays
always pass through F, they emerge parallel to the
20   optical axis. If sensor 36 is moved to focus
either image or to an intermediate position as
shown, the centers of the blur circles remain at
fixed points on the sensor albeit at different
heights.

25   A fortuitous and somewhat remarkable property
of image telecentric optics, as pointed out by R.
Kingslake, "Applied Optics and Optical
Engineering", Vol. II, p. 208, Academic Press,
1965, and M. Watanabe and S. K. Nayar,
30   "Telecentric Optics for Constant-Magnification
Imaging", Technical Report CUCS-026-95, Dept. of
Computer Science, Columbia University, New York,
NY, USA, September 1995, is that of a having a
constant effective f/# regardless of object/image
35   position. In a conventional optical system, the
effective f/# is increased as the image moves away
from the nominal (infinity) focal plane. As can

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be seen in Figure 1, the marginal ray, 19, from H2
crosses the axis at H2' farther away from the lens
than does the marginal ray, 18, from H1 at H1',
thus reducing the cone angle of the emergent beam
5   and, hence, increasing the effective f/# which is
defined as the ratio between the focal distance
and the diameter of the entrance pupil. Image
illuminance falls off as $1/(f/\#)^2$.

In an image telecentric system, it can be
10   shown that the marginal rays, 38 and 39, as
illustrated in Figure 3, emerge parallel to each
other for any pair of object/image distances, thus
keeping constant the ratio of the focal length to
the diameter of the entrance pupil. Note that the
15   entrance pupil diameter goes up with corresponding
nearer object position and farther image position,
thus keeping the ratio constant. This constant
effective f/# results in constant illuminance of
the image regardless of object position if the
20   object is illuminated in a consistent manner along
the length of the axis.

Referring now to Figure 4, the doubly
telecentric optical system in accordance with the
invention will now be discussed. As in Figures 2
25   and 3, Figure 4 also shows two objects H1, H2 of
equal size at different locations S1, S2 which are
of differing distance from the objective M1 of the
optical system. These two objects can be the same
object at two different axial positions or two
30   points of a single object as explained above for
Figure 1. Again, objective element M1 has front
and rear focal points F1, F1', respectively. Lens
L1 is, again, the objective lens of a camera
portion C and has front and rear focal points F2,
35   F2' respectively. As discussed above, M1 and L1
are located such that the front focal point F2 of
lens L1 coincides with the rear focal point F1' of

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objective element M1, where aperture A1 is
located.

    By following the principal rays from H1 and
H2 through the doubly telecentric optical system

5   of Figure 4, it can be seen that focused images
H1', H2' will be formed at different locations
behind lens L1 but both images will be of the same
size. Therefore, the doubly telecentric optical
system in accordance with the invention will

10   produce images of constant size and resolution
regardless of distance between an object of
interest and the lens and regardless of focus. In
other words, the doubly telecentric optical system
in accordance with the invention can be focused on

15   an object over a substantial range of distances
from the lens by movement of the imaging sensor
without change of magnification or resolution.

    The inventor has recognized that this
property of the invention allows constant

20   magnification and resolution imaging over a much
larger range of distances than is possible with
either object or image telecentric optical
systems. Further, the inventor has recognized
that constant magnification and resolution can be

25   obtained over this much increased depth consistent
with capturing well-focused images since
alteration of focus does not alter magnification,
as is the case with object and image telecentric
optical systems.

30   The inventor has also discovered additional
properties of the doubly telecentric optical
system in accordance with the invention which
allow improved automated imaging for numerous
applications and may not have been previously

35   recognized. Specifically, as alluded to above,
the effective f-number of the doubly telecentric
optical system does not change with focus as is

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characteristic of at least image telecentric
optical systems. Furthermore, it can be shown
that the hybrid system does not suffer from the
$\cos^4 \theta$ fall-off of image illuminance characteristic

5   of a traditional optical system since the
principal rays are parallel to the optical axis in
both object and image space and therefore
perpendicular to the object and image planes
respectively, thereby eliminating any angular

10 dependence, thus providing a substantially more
uniform image.

Further, there is a constant field of view
over the entire range of focus of the doubly
telecentric optical system. Therefore, features

15 of an object which would be within the field of
view at any given distance from the lens are not
cut off if the object is close to the lens. In
this regard, since resolution is constant with
object distance from the lens no additional image

20 processing is required to compensate for changes
in resolution or magnification and the
computational burden/overhead for doing so is
avoided. No image data is lost or discarded in
compensating for resolution variation, and

25 therefore no aliasing is introduced as a result of
subsampling, and performance of OCR, BCR, feature
extraction or other machine vision software is
improved. Furthermore, since no time is required
for image processing to compensate for change of

30 magnification and/or resolution, overall image
processing time is significantly reduced and
systems or devices controlled by such machine
vision systems can be operated at increased
throughput levels. Since resolution is constant

35 at all distances there is no need to increase scan
line rate at nearer distances which would
otherwise place further restraints on throughput

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due to sensor bandwidth limitations.

A generalized system controlled by a machine vision system employing the invention is schematically depicted in Figure 5, which also

5   depicts a preferred form of the invention. However, it should be understood that the system illustrated in Figure 5 is to be regarded as exemplary and, to the extent Figure 5 may reflect a particular application, the invention is not to

10 be considered as limited thereto, either in regard to the type of machine vision employed (e.g. OCR, BCR, feature extraction, metrology, etc.) or overall system function (e.g. article sorting, automated inspection, measurement, guidance,

15 etc.). Nevertheless, selective transport of articles 15 is depicted in Figure 5 in the interest of clarity and to illustrate not only overall architecture of a generalized system but also the need in some environments for well-

20 focused imaging over large differences in lens to object distance.

In the exemplary system illustrated in Figure 5, articles 15 of random dimensions (e.g. 15') are illustrated as being transported by conveyor 50.

25 A second conveyor 52 is controlled by the machine vision system 54 including the doubly telecentric optical system 100 in accordance with the invention. Information or features of interest are assumed to be on the top side of the

30 respective objects. In this regard, it should be recognized that the orientation of the objects and features of interest and the corresponding orientation of the optical system may be arranged in any desired manner. However, the location of

35 the features of interest relative to the camera lens cannot be regulated without the provision of a transparent structure against which the feature

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of interest is made to bear. Such a transparent
structure may damage the objects, is subject to
damage and wear and is difficult to maintain (e.g.
because of smearing or depositing of dirt or other
5   materials).

Since the objects 15 may be of essentially
random size within a relatively wide range, as
depicted, the height of the feature of interest
and the distance from the optical system will vary
10   widely. As alluded to above, a feature of
interest having a given size (e.g. a three inch by
five inch address label) on an object of low
height may easily fit within the field/angle of
view of a conventional lens but may exceed the
15   field/angle of view on a tall object. That is, in
terms of a conventional, non-telecentric lens, an
area of given dimensions, when close to the lens,
will subtend a greater angle that may exceed the
angle of view of the lens and/or sensor. By the
20   same token, with a conventional lens the image
will be larger and the resolution higher when the
feature of interest is close to the lens.
Features of interest may also be located on
different sides of the object and keystone
25   distortion of conventional lenses will complicate
image processing if the optical system is arranged
to view the objects from oblique angles in order
to view two or more sides of the object with the
same optical system and sensor.
30   Optical system 100, discussed above with
reference to Figure 4 (in which M1 is depicted in
a generalized form), preferably utilizes a concave
strip mirror 11 as the objective element of the
doubly telecentric optical system. The strip
35   mirror 11 should have a width sufficient to
accommodate the dimensions of a line scan or area
scan sensor 13 in the camera portion C of the

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optical system. (The type of image sensor
utilized in the camera C is not important to the
practice of the invention.) The shape of the
concave strip mirror is preferably spherical. The
5   arc length across the ends of the strip mirror 11
determines the field of view of the doubly
telecentric optical system and may be arbitrarily
large. Use of a mirror is preferred since the
folded catadioptric light path reduces overall
10 dimensions of the optical system and a very large
mirror can be made for a fraction of the cost of a
refracting lens only a few inches in diameter.

Concave objective mirror 11 is preferably
oriented at an angle to the axis of the remainder
15 of the doubly telecentric optical system 100 to
avoid imaging the optical system itself. The
remainder of the light path LP may be directed at
will, using angled (possibly moveable for
scanning) preferably planar mirrors (e.g. 10).
20 The system of Figure 5 preferably includes a
rangefinder or focus detection arrangement 110,
the type and configuration of which is
substantially unimportant to the practice of the
invention and could be located in camera C or
25 externally such as a light curtain or other
dimensioning device. The output of the
rangefinder or focus detection system is used to
control axial shifting of the location of the
image sensor 13 of camera C to allow capture of a
30 well-focused image.

Focus adjustment by means of a moving sensor
is preferable to that by a moving lens which is
slow, less reliable, and much more complicated,
since the relation of the lens to the auxiliary
35 objective must remain fixed. Numerous
arrangements will thus be apparent to those
skilled in the art and the details thereof are not

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important to the practice of the invention. On
the other hand, for some applications where the
optical path can be made long and the range of
focus suitably limited, focusing by lens motion

5   may cause a change in resolution which may be
acceptably limited.

Accordingly, a feature of interest on each
object 15 will be imaged by camera C and optical
system 100 as the object is transported by

10   conveyor 50 and illuminated by light source LS.
(Alternatively, a light source could be provided
to illuminate the objects along light path LP.)
The image of the feature will be well-focused as
well as being of constant magnification and

15   resolution and consistent field of view, indicated
by chain lines 55, over the entire focus range.
The corresponding image data can thus represent
the full resolution of which the optical system
and image sensor are capable of producing, thus

20   providing for high performance of the image
processing software, in terms of accuracy.

Since resolution is constant, there is no
need to increase scan line rate in order to
maintain a constant aspect ratio as the object

25   position gets nearer to the objective, thus
reducing data output for nearer objects and/or
allowing higher data rates for all object sizes.
Since the image data is of constant resolution and
magnification and not distorted by perspective

30   (and not segmented for tall packages due to the
field of view) the image processing for character
recognition, bar code identification, measurement,
feature extraction and the like can be executed in
reduced time since no preprocessing of data to

35   accommodate variation of magnification and/or
resolution need be performed. By the same token,
the optical system can be oriented to view more

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than one side of the object and the images will be
orthographic and free of perspective distortion.

In this regard, the preprocessing to correct
for perspective distortion or variation in
5   magnification and resolution represents a
processing burden of a magnitude similar to or
even substantially greater than that of metrology,
character recognition or feature extraction.
Therefore, a result of the image processing may be
10   available in a fraction (e.g. less than one-half)
of the time which would be required without the
avoidance of preprocessing in accordance with the
invention. This feature of the invention allows
the substantial meritorious effect of potentially
15   multiplying (e.g. doubling or tripling) throughput
of an expensive controlled system; greatly
reducing the cost per operation thereof.

Since the overall system may be very
expensive, such an increase in throughput, alone,
20   would justify a very substantial cost of the
optical system which also provides further
performance benefits as described above. However,
the use of a concave mirror in accordance with a
preferred form of the invention allows an optical
25   system that supports the above-described
advantages to be provided very inexpensively and
at a cost comparable to conventional optics (e.g.
by the addition of an aperture plate and a curved
mirror, suitably located, to existing optics in
30   the system).

Image processor 56 receives image (pixel)
data from the image sensor 13 of camera C and
provides processing in accordance with the image
to derive desired information. The type of
35   processing is unimportant to the practice of the
invention. However, it is important to recognize
that the invention including a doubly telecentric

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optical system provides qualitatively and
quantitatively enhanced performance from any
software used, including existing software. That
is, the optical system in accordance with the
5 invention can be retrofitted into existing systems
and will substantially improve throughput and
accuracy thereof without additional modification.

The output of the processor is provided to a
controller 58 which may be of any type or
10 configuration suitable for the apparatus that it
is to control. In the exemplary, generalized
system of Figure 5, a second conveyor 52 is
provided that can be driven in either of two
directions (e.g. into or out of the plane of the
15 page) for sorting of objects 15 in accordance with
the imaged feature. Further such additional
conveyors (or their counterparts in other
environments and applications) could be provided
and controlled in accordance with a single imaging
20 of the feature of interest and corresponding image
processing thereof. For example, the OCR of zip-
code information could control sorting into as
many groups as may be desired and supported by the
information.

25   In view of the foregoing, it is seen that the
invention provides an optical system having
numerous properties uniquely suited to many forms
and applications of machine vision, including
constant size and resolution while accommodating
30 large variation in lens to object distance and
consistent with focusing, avoidance of variation
in light gathering or transmission with focus and
consistent field of view over the full range of
focus. The invention avoids preprocessing of
35 image data to alter effective resolution and/or
magnification to compensate for variation thereof
(as would be characteristic of and required by

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other optical systems) and allows image processing
at the full resolution delivered by the optical
system for increased accuracy while increasing
throughput of the controlled system. The optical

5   system can be retrofitted into existing systems
without further modification (and potentially by
addition of only two inexpensive optical elements)
to produce substantially enhanced performance of
such existing systems.

10   While the invention has been described in
terms of a single preferred embodiment, those
skilled in the art will recognize that the
invention can be practiced with modification
within the spirit and scope of the appended

15   claims.